Performance of Planning Systems

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Planning is learning from experience in the domain of imagination.
From the Section 10 of this paper

The goal of this paper is to help in the organization of further research in the area of Planning.

1. Emergence and Development of the Theoretical Domain on Planning

The area of planning is a victim of linguistics: professionals of different domains give different interpretation to the phenomenon of "planning." Traditionally, it was associated with human activities and the help of science was expected

a) in a better organization of information for planning supporting the way the humans plan

b) in proposing of techniques that help to come up with "interesting" alternatives of planning decisions

c) in structuring the process of planning so that to make it more efficient

d) in modeling human activities during the process of planning.

Simon and Newell were the first that visualized planning as an element of each problem solving process. However, AI treated planning in the way it treated other problems - with the help of toy-problems (like Hanoi-Tower and block-world situations.

Specialists in control did not realize and did not appreciate the fact that feedforward control is actually the result of planning. The elegant discoveries of Nilsson and Fikes in their heuristic search methods remained unnoticed by control community until recently.

Specialists in automation of therapeutic solutions did not realize that they plan the process of disease development and plan the process of healing.

Specialists in education did not realize that proposing a curriculum and/or a particular syllabus has no difference from the processes of feedforward control and process of disease development and healing.

Specialists in optimization (re: operation research) did not realize that their problems were just elements of the planning theory.

Specialists in cognitive psychology seldom saw anything in common between "planning" and "imagination."

Thinkers of finding the goal did not have anything in common with thinkers computing schedules of goal achievement.

A common wisdom about planning was (and is) that there are many ways of planning and each of them has its place.

The following linkages were totally neglected:

a) the linkage between off-line planning and on-line control,

b) the linkage between specifying the goal and finding a schedule of achieving the goal.

c) the linkage between the linguistics of finding the image of "goal" and searching of the best schedule.

d) the linkage between the methodology and the *performance of planning*.

2. Planning for Behavior Generation

Robotics became the integrated domain that provided for blending the goals and testing the means of achieving them, i.e. a domain with a direct need for planning. In 1983, T. Lozano-Perez has introduced the idea of search in "configurations space". From the experience of using this search, it became clear that the exhaustive search would be computationally prohibitive if the configuration space is tessellated with the accuracy required for motion control. But his theory made two important thing obvious: 1) planning is an apogee of *creating admissible alternatives* and searching for the trajectories entailed by these alternatives. 2) planning is performed upon *milestones in the state space*, and if they do not exist in the reality, they should be created artificially (re: centers of the tessellata in the configuration space).

This development helped to realize that planning should combine the exhaustive (or meaningfully thorough) search off-line, and an efficient algorithm of an off-line control. It was about of this time that we stopped talking about control of actions and introduced a more balanced term of Behavior Generation. The latter became a codeword for the joint process of arranging and testing the alternatives within the mechanism of "planning" (open loop, feedforward control) blended with the on-line finding the alternatives of feedback for error compensation (closed-loop control, or "execution").

Behavior Generation alludes to many mechanisms of planning and execution. At the present time, these mechanisms cannot be considered as known thoroughly, and the general theory of planning can hardly be immediately attempted. There is a merit in discussing a subset of problems in which the goal is determined as attainment of a particular state.

The following are scattered notes on the progress in the domain of planning.

- Most of the realistic problems can be translated into this paradigm. Other types of realizations can also be imagined: in chess the goal is clear (to win) but this goal cannot be achieved by achieving a particular position in a space (even in a descriptive space.) Most of the problems related to the theory of games and linked with pursuit and evasion are characterized by a similar predicament.
- Let us notice the following: no matter what is the domain of decision making, the process of planning can be performed only by searching the state space and thus, determining both the final goal, and the trajectory of motion leading to this goal.
- In 1981 J. Albus has introduced the methodology of task decomposition for hierarchical systems which has grown into a NIST-RCS methodology.
- In 1981 G. Giralt outlines the concept of planning for mobile robots via tessellated space.
- In 1983, T. Lozano-Perez has introduced search in Configuration Space.
- In 1986, A. Meystel has demonstrated (CDC, Athens) that the most efficient functioning of a multilevel learning/control systems can be provided by a proper choice of a ratio of lower level/higher level of resolution. This concept of planning/control becomes a strong theoretical support for the hierarchical architecture of intelligent system control developed by J. Albus during the period of 1980-1998.
- In 1985-87 M. Arbib's school of control via "schemata" came up with a numerous schemes of "reactive" behavior. This gave birth to a multiplicity of robot control concepts which explore and exercise reactive behavior generation.
- In the meantime, the primary focus of robotics shifts to the area of systems which do not require any planning (robotics with "situated behavior"). Thus, the interest in planning diminishes (R. Brooks, MIT, R. Arkin, Georgia Tech) and the curiosity of researchers shifts toward emerging phenomena in non-intelligent robots.

3. Planning in a Representation Space with a Goal

This is an outline of the common methodology of planning pertaining to most of the disciplines and areas of application. The *world* is assumed to be judged upon by using its State Space (or the Space of Representation) which is interpreted as a time tagged vector space with a number of important properties. Any activity (motion) in the World (Space of Representation) can be characterized by a trajectory of motion along which the "working point" or "present state" (PS) is traversing this space from one point (initial, or state, IS) to one or many other states (goal states, GS.) The goal states are given initially from the external source as a "goal region", or a "goal subspace" in which the goal state is not completely defined in a general case.

From the point of view of planning, state space does not differ from the configuration space. Indeed, the upcoming behavior is represented as a trajectory in the state-space (and/or configuration space). One of the stages of planning (often the initial one) is defining where exactly is the GS within the "goal region." In this paper, we will focus upon planning problems in which one or many GS remain unchanged through all period of their achievement. Traversing from IS to GS is associated with consuming time, or another commodity (cost). So, the straight-forward exhaustive search is feasible which allows for exploring all possible alternatives.

Researchers in the area of reactive behavior introduced a method of potential fields for producing comparatively sophisticated obstacle avoiding schemes of motion. Reactive behavior is considered to be an anti-thesis for planning. It is not so. Planning based motion can be called reactive, too. The difference is that in the papers on reactive behavior, we react to the present situation. In the system with planning, we react too: but we react to the anticipated future.

Thus, planning can be considered an *anticipatory reactive behavior.* The difference is in the fact that anticipation requires representation richer than the simple reactive behavior requires. The philosophy of the approach affects the performance of planning.

4. Types of Representation Available

All Representation Spaces are acquired from the external reality by the processes of Learning. Many types of learning are mentioned in the literature (supervised, unsupervised, reinforcement, dynamic, PAC, etc.) Before classifying a need in a particular method of learning and deciding how to learn, we would like to figure out what exactly we should learn. Can the process of learning be separated into two different learning processes:

- that of representation, and
- that of the rules of action,

or are these two kinds of learning just two sides of the same core learning process?

The following knowledge should be contained in the Representation Space. If no GS is given, any pair of state representations should contain implicitly the rule of moving from one state to another. In this case, while learning we inadvertently consider any second state as a provisional GS.

We will call "proper" representation a representation similar to the mathematical function and/or field description: at any point the derivative is available together with the value of the function; the derivative can be considered an action required to produce the change in the value of the function.

We will call "goal oriented" representation a representation in which at each point a value of the action is given required for describing not the best way of achieving an adjacent point but the best way of achieving the final goal.

Both "proper" and "goal oriented" representations can be transformed into each other. However, they differ in the productivity of planning.

5. Components of Representation Space

Representation (that of the World) can be characterized by the following artifacts:

- existence of states with its boundaries determined by the resolution of (each state is presented as a tessellatum, or an elementary unit of representation, the lowest possible bounds of attention)
- characteristics of the tessellatum which is defined as an indistinguishability zone (we consider that resolution of the space shows how far the "adjacent" tessellata (states) are located from the "present state" (PS)
- lists of coordinate values at a particular tessellatum in space and time
- lists of actions to be applied at a particular tessellatum in space and time in order to achieve a selected adjacent tessellatum in space and time
- existence of strings of states intermingled with the strings of actions required to receive next consecutive tessellata of these strings of states
- boundaries (the largest possible bounds of the space) and obstacles
- costs of traversing from a state to a state and through strings of states.

In many cases, the states contain information which pertains to the part of the world which is beyond our ability to control it, and this part is called "environment." Another part of the world is to be controlled: this is the system for which the planning is to be performed. We will refer to it frequently as "self." Thus, a part of the representation is related to "self" including knowledge about actions which this "self" should undertake in order to traverse the environment.

It is seen from the list of artifacts that all knowledge is represented at a particular resolution. Thus, the same reality can be represented at many resolutions and the "multiresolutional representation" is presumed.

The system of representation is expected to be organized in a multiresolutional fashion. This will invoke the need in applying a number of special constraints and rules. The rules of inclusion (aggregation/decomposition) are especially important.

6. Planning in Redundant Systems

Non-redundant systems have a unique trajectory of motion from a state to a state. Redundant system is defined as a system in which there is more than one trajectory of motion from one state to another. It can be demonstrated for many realistic couples "system-environment" that

- they have a multiplicity of traversing trajectories from a IS to a GS
- these trajectories can have different costs.

These systems contain a multiplicity of alternatives of space traversal. Redundancy grows when the system is considered to be a stochastic one. The number of available alternatives grows even higher when we consider also a multiplicity of goal tessellata of a particular level of resolution under the condition of assigning the goal at a lower resolution level which is the fact in multiresolutional systems (such as NIST-RCS.)

In on-redundant systems there is no problem of planning. Since the trajectory of motion to be executed is a unique one, the problem is to find this trajectory and to provide tracking of it by an appropriate classical control system.

7. Learning as a Source of Representation

Learning is defined as knowledge acquisition via experience of functioning. Thus, learning is development and enhancement of the representation space under various goals. The representation can be characterized in the following ways:

- by a set of paths (to one or more goals) previously traversed

- by a set of paths (to one or more goals) previously found and traversed
- by a set of paths (to one or more goals) previously found and not traversed
- by a totality of (set of all possible) paths
- by a set of paths executed in the space in a random way.

One can see that this knowledge contains implicitly both the description of the environment and the description of the actions required to traverse a trajectory in this environment. Moreover, if some particular system is the source of knowledge, then the collected knowledge contains information about properties of the system which moved in the environment.

All this information arrives in the form of experiences which record states, actions between each couple of states, and evaluation of the outcome. The collection of information obtained in one or several of these ways forms knowledge of space, KS.

If the information base contains all tessellata of the space with all costs among the adjacent tessellata - we usually call it the “a complete representation.” The tessellation can be a randomized one: a factor strongly affecting the performance.

Thus, the representation is equivalent to the multiplicity of explanations how to traverse, or how to move. In other words: all kinds of learning mentioned in p. 3 are equivalent.

Comments: a) Knowledge of the space (KS) is realized via knowing states, and/or knowing the "derivatives" (or actions) from a state to a state.

b) Apparently, each state can be characterized by some cumulative cost (value), while each traversal from a state to a state can be characterized by some incremental cost (goodness of a move or a set of moves.)

8. Standardizing the Problems of Planning

Any problem of planning is associated with

- actual existence of the present state
- actual, or potential existence of the goal state
- knowledge of the values for all or part of the states as far as some particular goal is concerned.

From this knowledge the cumulative costs of trajectories to a particular goal (or goals) can be deduced. On the other hand, the knowledge of costs for the many trajectories traversed in the past can be obtained which is equivalent to knowing cumulative costs from the initial state (PS) to the goal state (GS) (from which the values of the states can be deduced.)

In other words, any problem of planning contains two components: the first one is to determine and/or to refine the goal (bring it to the higher resolution.) The second one is to determine the motion trajectory to this refined goal. These two parts can be performed together, or separately. Frequently we are dealing with them separately. In the latter case they are formulated as follows:

a) given PS, GS and KS (all paths) find the subset of KS with a minimum cost, or with a pre-assigned cost, or with a cost in a particular interval.

b) given PS and GS from the lower resolution level and KS (all paths) find the GS with a particular value (which is satisfactory for the system).

9. Performance of Planning Algorithms

Finding solutions for these problems is done by a process that is called *planning*. In other words, planning is construction of the goal states, and/or strings of states connecting the present state with the goal states. Performance of planning algorithms is determined by the way these procedures are arranged.

The first component of the planning algorithm is translation of the goal state description from the language of low resolution to the level of high resolution. Frequently, it is associated with increasing of the total number of the state variables. In all cases it is associated with reduction of the indistinguishability zone, or the size of the tessellatum associated with a particular variable.

The second component is the simulation of all available alternatives of the motion from the initial state, IS to one or several goal states, GS and selection of the "best" trajectory. Procedurally, this simulation is performed as a search, i.e. via combinatorial construction of all possible strings (groups). To make this combinatorial search for a desirable group more efficient we reduce the space of searching by focusing attention.

Thus, all planning algorithms consist of two components: a) a module for exploration of spatial distribution of the trajectory, and b) a module for exploration of the temporal distribution. No algorithm of planning is conceivable without these two components.

The need in planning is determined by the multialternative character of the reality The process of planning can be made more efficient by using appropriate heuristics which is not considered in this paper.

10. The Relations Between Planning and Learning

Planning is learning from experience in the domain of imagination. Planning is performed by searching within a limited subspace

- for a state with a particular value (designing the goal)
- for a string (a group) of states connecting SP and GP satisfying

some conditions on the cumulative cost (planning of the course of actions)

The process of searching is associated ether with collecting the additional information about experiences, or with extracting from KS the implicit information about the state and moving from state to state, or learning. In other words, planning is inseparable from and complementary to learning.

This unified planning/learning process is always oriented toward improvement of functioning in engineering systems (improvement of accuracy in an adaptive controller) and/or toward increasing of probability of survival (emergence of the advanced viruses for the known diseases that can resist various medications, e.g. antibiotics.)

Thus, this joint process can be related to a system as well as to populations of systems and determines their evolution.

11. Other Components of Planning

Planning algorithms consist of the procedures of Job Assignment and Scheduling. Job Assignment distributes the motion among the spatial coordinates. Scheduling distributes the motion along the time axis. Together, they contribute to the search process. Search is performed by constructing feasible combinations of the states within a subspace. ("Feasible" means: satisfying a particular set of conditions.) Search is interpreted as exploring (physically, or in simulation) as many as possible alternatives of possible motion and comparing them afterwards.

Each alternative is created by using a particular law of producing the group of interest (cluster, string, etc.) Usually, grouping presumes exploratory construction of possible combinations of the elements of space (combinatorial search) and as one or many of these combinations satisfy conditions of "being an entity" - substitution of this group by a new symbol with subsequent treating it as an object (grouping.)

The larger the space of search is the higher is the complexity of search. This is why a special effort is allocated with reducing the space of search. This effort is called focusing attention and it results in determining two conditions of searching, namely, its upper and lower boundaries:

a) the upper boundaries of the space in which the search should be performed, and

b) the resolution of representation (the lower boundaries)

12. Planning Embodies the Intelligence of a System

Formation of multiple combinations of elements (during the search procedure, S) satisfying required conditions of transforming them into entities (grouping, G) within a bounded subspace (focusing attention, F) is a fundamental procedure in both learning and planning. Since these three procedures work together we will talk about them as about a triplet of computational procedures which include grouping, focusing attention and search (GFS.) Notice, that in learning it creates lower resolution levels out of higher resolution levels (bottom-up) while in planning it progresses from the lower resolution levels out of higher resolution levels (top-down.)

This triplet of computational procedures is characteristic for intelligence and probably is the elementary computational unit of intelligence. Its purpose is transformation of large volumes of information into a manageable form which ensures success of functioning. The way it functions in a joint learning-planning process explains the pervasive character of hierarchical architectures in all domains of activities.

The need in GFS is stimulated by the property of knowledge representations to contain a multiplicity of alternatives of space traversal (which is a property of representations to be redundant.) Redundancy of representations determines the need in GFS: otherwise the known systems would not be able to function efficiently (it is possible that redundancy of representations is a precondition for the possibility of Life and the need in Intelligence)

13. Planning is Inseparable From Control

Development of a plan is equivalent to computing the "feedforward control." To compute FFC, we have to have a model of a system (representation) and apply an operation if inverse (computing the required FFC control commands for the motion preassigned). Even if a system representation is in a not-invertible form, the inverse can be found by a forward searching.

Representations reduce the redundancy of reality. Elimination of redundancy allows for having problems that can be solved in a closed form (no combinatorics is possible and/or necessary). Sometimes, this ultimate reduction of redundancy is impossible and the combinatorial search is the only way of solving the problem). If the problem cannot be solved in a closed form, we introduce redundancy intentionally to enable functioning of GFS (grouping, focusing attention, and searching).

At each level of resolution, planning is done as a reaction for the slow changes in situation which invokes the need in anticipation and active interference

a) to take advantage of the growing opportunities, or

b) to take necessary measures before the negative consequences occur.

The deviations from a plan are compensated for by the compensatory mechanism also in a reactive manner. Thus, both feedforward control (planning) and feedback compensation are reactive activities as far as interaction system-environment is concerned. Both can be made active in their implementation. This explains different approaches in control theory.

Examples:

a) Classical control systems are systems with no redundancy, they can be solved in a closed form. Thus, they do not require any searching.

b) Any stochastics introduced to a control system creates redundancy and requires either for elimination of redundancy and bringing the solution to a closed form, or performing search.

c) Optimum control allows for the degree of redundancy which determines the need in searching.

Recently, an area of "supervisory control" has emerged as a partial introduction of the control theory to the domain of planning.

14. Research for Planning: Topics For Exploration and Discussion

The following research topics can be outlined:

a) development of the system of representation for planning purposes; it should provide for a multiresolutional organization of information

b) analysis of existing and potentially beneficial techniques of synthesizing the goal assignments (spatial plan distribution)

--by using combinatorial techniques (computer and human-based)

--by analytical methods (e.g. variational)

c) analysis of existing and potentially beneficial techniques of determining preferable clusters, or groups: determining the preferred schedules for strings of the way points, or milestones (temporal plan distribution)

--by using search in the state space

--by using game-theoretical methods

--by using self-organization of multiple agents

d) quantitative evaluation of the tools for narrowing attention: determining envelopes around the trajectory of motion (string of the milestone events) for the consecutive refinement (repetition of the planning procedure at the higher resolution level)

e) construction of the state spaces for the consecutive searching

f) analysis of the methodologies of state-space tessellation for applying different methodologies of consecutive refinement

g) exploring the methods of search applicable for determining the preferential strings

--by searching techniques induced by dynamic programming

--by standard techniques of exhaustive search

--by methods of heuristic guiding during the search

--by searching via evolutionary programming

--by searching in nonlinear problems

h) testing the results of planning via various simulation methodologies

i) exploring the phenomenon of nestedness of plans obtained at various resolutions (at various levels of resolution)

j) dealing with uncertainties of information

--by decision-making procedures when the values of alternatives are uncertain and do not allow for an unequivocal choice

--by development and maintenance of contingency plans

k) analyze the role of prediction in planning, develop a system of creating and using predictions

l) analyze the phenomenon of goal

m) determine methods of forming different functionals of "cost", or "goodness"

n) explore planning under condition of multiple criteria (costs)

o) test benefits and deficiencies of various schemes of decision-making in planning

p) the computer aspects of planning are virtually unexplored: do we need a language for planning?

All positions of this list affect the performance both of the system in the World and of planning algorithms as a part of the Design process.